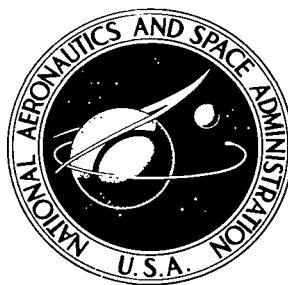


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**PROMOTION OF DROPWISE CONDENSATION
OF ETHYL ALCOHOL, METHYL ALCOHOL, AND
ACETONE BY POLYTETRAFLUOROETHYLENE**

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OF ETHYL ALCOHOL, METHYL ALCOHOL, AND ACETONE BY
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SUMMARY

The phenomenon of dropwise condensation, in which the condensate forms into drops rather than covering the entire cooling surface with a continuous film, produces heat-transfer coefficients as much as 2 to 10 times greater than those produced by filmwise condensation. Promotion of dropwise condensation is therefore desirable for increasing the effectiveness of condensing systems.

An experimental program has been performed in which promotion of dropwise condensation of several organic vapors is achieved by coating a bare iron tube with polytetrafluoroethylene (teflon). Data are presented in the form of overall heat-transfer coefficients for the dropwise condensation of ethyl alcohol, methyl alcohol, and acetone on the teflon-coated tube and for filmwise condensation on the bare iron tube. The overall heat-transfer coefficients during dropwise condensation are approximately 30 percent greater for ethyl alcohol, 45 percent greater for methyl alcohol, and 65 percent greater for acetone than those during filmwise condensation.

Carbon tetrachloride and trichlorofluoromethane were also condensed on the bare iron tube and on the teflon, but filmwise condensation occurred on both surfaces.

A study of previously reported experimental results shows that aniline, ethylene glycol, and nitrobenzene also condense dropwise on a teflon surface but benzene condenses filmwise.

Ethyl alcohol, methyl alcohol, acetone, aniline, ethylene glycol, and nitrobenzene, which all condense dropwise on the nonpolar teflon surface, are polar liquids. Carbon tetrachloride and benzene, which condense filmwise on a teflon surface, are nonpolar; trichlorofluoromethane, which also condenses filmwise, is slightly polar.

It is suggested that the possible relationship of dipole moment as an aid in predicting the type of condensation which will occur for organic liquids is worthy of further study.

INTRODUCTION

When a surface at a temperature below the saturation temperature of a vapor is exposed to that vapor, either saturated or superheated, liquid condensate forms on the surface. If the liquid wets the surface, it spreads out and establishes a stable film; consequently, the process is called filmwise condensation. Further vapor condenses on the liquid at the interface because of the heat transferred through the liquid film. With pure saturated vapor, the temperature at the liquid-vapor interface is also essentially the saturation temperature.

If the liquid does not wet the surface, droplets form and run down the surface, coalescing as they travel downward because of gravity forces. Little is understood about the mechanism of dropwise condensation or the associated heat-transfer process, except that heat-transfer rates are from 2 to 10 times those for filmwise condensation at the same temperature difference (ref. 1). Commercially, it is difficult to predict whether dropwise condensation will occur and difficult to maintain it for long periods of time. No known ordinary metallic surface, when clean, will produce dropwise condensation. To obtain dropwise condensation, metallic surfaces must be coated with a film of some substance that the liquid does not wet, or a suitable promoter may be injected into the condenser with the incoming vapor. Some promoters of dropwise condensation are the fatty acids, mercaptans, light hydrocarbon oils, and waxes. However, promoters of this type wash off the condensing surfaces rather quickly and usually last only for periods of several seconds or, in some rare cases, up to a maximum of several hundred hours (refs. 2 and 3).

The increased heat-transfer rate achievable with dropwise condensation is desirable in the design of commercial condensing equipment. However, because of the difficulty in predicting and maintaining dropwise condensation, such equipment is presently designed on the assumption that filmwise condensation will exist (ref. 4). Improvements in prediction techniques and development of a permanent promoter which may permit the design of condensers based on the occurrence of dropwise condensation are therefore highly desirable.

The purpose of this paper is to show that dropwise condensation of polar organic vapors can in some cases be achieved by coating the condensing surface with a thin layer of teflon (which is nonpolar) and to present data on the resulting increase in the overall heat-transfer coefficients compared with those for filmwise condensation.

Whether a liquid forms drops or a film on a surface is a problem which confronts researchers in the adhesives field as well as in the condensation field. Recent studies (ref. 5) in the adhesives field have shown that if a liquid adhesive forms drops on an adherend surface, poor bonding results, but if the liquid spreads and forms a film on the

adherend surface, good bonding is obtained. A brief discussion of the possible applicability of the adhesives-theory concept of critical surface tension and of the De Bruyne adhesion rule in predicting the occurrence of dropwise condensation is therefore included.

SYMBOLS

A_i	cooling-water cross-sectional flow area
A_s	surface area of condenser tube
c_p	specific heat of water
Q	heat added to water
T_{v1}	vapor temperature at inlet to condenser
T_{v2}	vapor temperature at outlet from condenser
T_{w1}	cooling-water temperature at inlet to condenser
T_{w2}	cooling-water temperature at outlet from condenser
ΔT_m	logarithmic mean temperature difference
U	overall heat-transfer coefficient
V	cooling-water velocity
w	cooling water flow rate
γ_c	critical surface tension
γ_{lv}	surface tension at interface between liquid and vapor
γ_{sl}	surface tension at interface between solid and liquid
γ_{sv}	surface tension at interface between solid and vapor
θ	contact angle of liquid droplet

REVIEW OF DROPWISE CONDENSATION THEORY

The occurrence of dropwise condensation in heat exchangers has been studied for more than 40 years; however, its mechanism is not understood and no explanations have been widely accepted. A summary of several theories concerning the mechanics of dropwise condensation is given by Rohsenow and Choi (ref. 4) as follows. It has generally been supposed, but not proven, that most of the heat goes through the bare surfaces existing between drops. If this is what occurs, the means by which the condensed vapor reaches existing drops or forms into drops is not yet known. It has been suggested that violent eddy currents set up by rapid condensation might move subcooled vapors from the vicinity of the bare areas toward the surrounding drops. An alternate suggestion is that condensation occurs on the surface of the drops and that heat is conducted through the drops only. Recent studies by Umur and Griffith (ref. 6) indicate that no film greater than a monolayer in thickness exists on the area between drops, and that no net condensation takes place on the area between the drops.

All these theories (refs. 4 to 6) are concerned with the mechanism and dynamics of how dropwise condensation occurs and the means of explaining the rate of drop growth to determine why heat-transfer rates are greater than for filmwise condensation.

Another segment of the literature recognizes the fact that heat-transfer rates are greater for dropwise condensation and is concerned with determining how much greater the heat-transfer rate is and how to promote dropwise condensation. This is the segment of the literature which will now be discussed and the segment in which the present paper should be included.

Blackman et al. (ref. 3) investigated many different compounds as potential promoters of dropwise condensation of steam by applying them to the condensing surface. They found that all promoters which gave ideal dropwise condensation contained a nonpolar hydrocarbon chain. Poor dropwise condensation was obtained with promoters composed of two approximately equal polar and nonpolar groups, and complete filmwise condensation occurred with promoters which contained only polar groups.

The effectiveness of teflon as a promoter of dropwise condensation of steam has been demonstrated in reference 7. Topper and Baer (ref. 8) also used teflon as a condensing surface and obtained dropwise condensation of aniline, ethylene glycol, and nitrobenzene, which are polar, but they obtained filmwise condensation with benzene, which is nonpolar. Several others (refs. 9 to 13) have investigated dropwise condensation of organic vapors on various types of promoted surfaces. However, none of these studies (refs. 7 to 13) mentioned the possible significance of the relationship between the dipole moment of the liquids and that of the nonpolar condenser surfaces in producing dropwise condensation.

The selection of promoters has evolved mostly through trial and error over many years of testing. Explanations of why certain promoters are effective are usually not given or they are discussed from the viewpoint of surface wetting (ref. 14). Because such explanations fail to predict in all cases when a surface will be wetted and when it will cause dropwise condensation, they are inadequate, and new approaches are needed for improved understanding of promoters and how and why they are effective.

As late as 1961, Grober et al. (ref. 14) stated, "For many organic vapors which wet metallic surfaces thoroughly no suitable promoters have as yet been found." They also stated that it would be pointless to attempt to prescribe the conditions under which dropwise condensation can occur since the conditions are not sufficiently defined to permit reproducible results. The wettability of a surface could be measured in terms of the contact angle θ of a droplet (fig. 1), but measurement of this angle is difficult because of a dependence on previous history (e.g., absorption of foreign molecules and prior drying in air). In addition, reference 14 points out that when a droplet is moving, the contact angle at the forward and aft edges is different.

Investigations of how to achieve dropwise condensation have been no more successful than those concerned with understanding the rates and mechanisms involved after dropwise condensation has been achieved.

REVIEW OF RELATED ADHESIVES THEORY

The De Bruyne adhesion rule (ref. 15) is an often-used empirical rule. One part of this rule says that strong bonding between liquid adhesives and solid surfaces cannot be formed between nonpolar surfaces and polar adhesives. The polar liquid adhesive forms drops on a nonpolar surface and does not produce the film required for good bonding. There may be a similar relationship in dropwise condensation where polar organic liquids form drops on a condensing surface of teflon, which is nonpolar. Reference 5 points out that the other part of the De Bruyne adhesion rule, that is, good bonding cannot occur between nonpolar adhesives and polar surfaces, is not always correct.

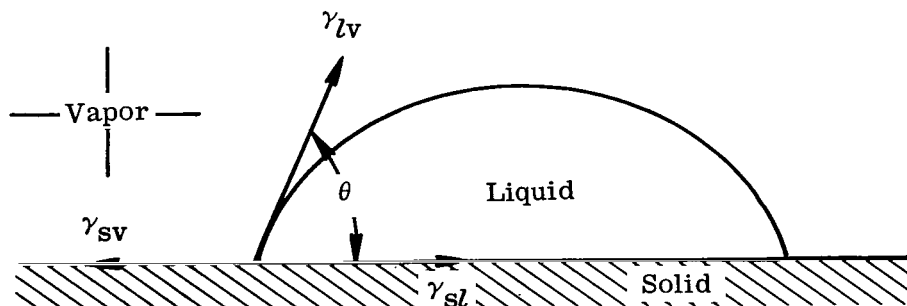


Figure 1.- Vector diagram for surface tension of a liquid on a horizontal surface (from ref. 14).

Whether a liquid forms drops or not on a solid surface is therefore a problem confronting researchers in the adhesives field. Considerably more effort has been expended in adhesives research than in dropwise condensation. This heretofore unrecognized source of information may be valuable in gaining a better understanding of the promotion of dropwise condensation.

Low- and High-Energy Surfaces

Every solid surface has associated with it a surface-free energy, or a surface tension. Numerically they are equivalent. The former, a scalar quantity, is the energy required to produce a unit area of new surface; the latter is the force per unit length required to expand the surface. It has been convenient in the field of adhesives to use the terms "high energy" and "low energy" for the two extremes of the surface-free energies of solids (ref. 15). The surface-free energies of most liquids are less than 100 ergs/cm² at ordinary temperatures. But hard solids have surface-free energies from approximately 500 to about 5000 ergs/cm², the values being higher for hard materials with high melting points. Examples are the ordinary metals, glass, and diamond. In contrast, soft solids have lower melting points, and their surface-free energies are usually under 100 ergs/cm². Examples are waxes and most solid organic polymers.

Because of the relatively low surface-free energies of organic liquids, they would be expected to spread easily on solids of high surface energy since a large decrease in the surface-free energy of the system would result, and this is usually found to be true. However, the surface-free energies of such liquids are comparable with those of low-energy solids. Therefore, systems which tend to form drops are most commonly found among such combinations. Research has shown (ref. 15) that when a low-energy liquid forms drops on a high-energy surface, an adsorption of the liquid on the solid had taken place before or during contact, making it behave as a low-energy surface.

Critical Surface Tension

Another concept from the field of adhesives is the critical surface tension of wetting (ref. 15). Studies of contact angles for a variety of pure liquids on low- and high-energy surfaces have shown that a rectilinear relation exists between the cosine of the contact angle θ (fig. 1) and the surface tension γ_{LV} for a series of homologous organic liquids on a specific surface. Critical surface tension γ_c is defined as the intercept of the horizontal line $\cos \theta = 1$ with the straight-line plot of $\cos \theta$ against γ_{LV} . (See fig. 2.)

Figure 2, as reproduced from reference 15, illustrates the behavior for the series of liquid n-alkanes on a teflon surface. The alkane liquids with lower surface tensions have a smaller contact angle and wet the surface. For all values of surface tension of the liquids below a critical value γ_c , the contact angle is zero and complete wetting

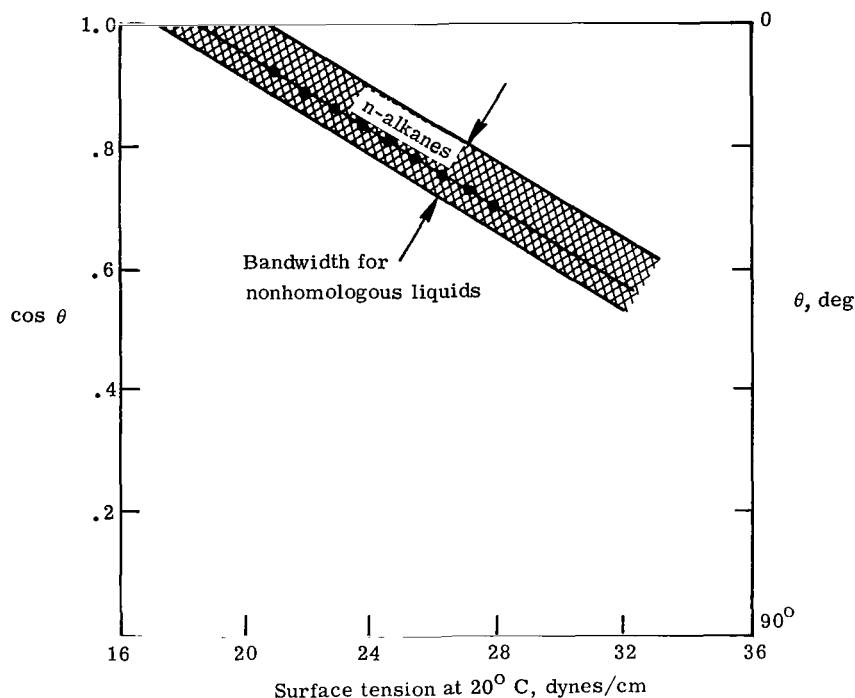


Figure 2.- Contact angle of drops as a function of surface tension (from ref. 15).

occurs. Above the value of γ_c , drops form. The intercept of the graph in figure 2 shows that the critical surface tension of n-alkanes on the teflon surface is 18.5 dynes/cm.

Even when $\cos \theta$ is plotted against γ_{lv} for a variety of nonhomologous liquids, the data points lie close to a straight line or tend to collect around it, as shown by the shaded area of figure 2. Reference 16 gives the critical-surface-tension range for nonhomologous liquids on teflon at 20° C as 17.5 to 20.5 dynes/cm. Although this is not as clearly definitive as for a homologous series, it does indicate that at 20° C, liquids with surface tensions below 17.5 dynes/cm should form drops. The wetting characteristics of liquids between 17.5 and 20.5 dynes/cm cannot be predicted except for the n-alkanes. The critical surface tension has been found useful as an empirical parameter for relative characterization of the surface-free energy of a solid.

Dipole Moment

If a body suspended on an axis is acted upon by a force normal to the axis, the product of the magnitude of the force and the length of the lever arm from the rotational axis to the point of force application is called the moment of the force. Similarly, if a minute bar of length l has a positive charge e on one end and an equal negative charge on the other, the electric or dipole moment of the bar is le . If the electrons around the nucleus of an atom are symmetrically arranged, the electrical center coincides with the nucleus

and the atom is nonpolar. If the electrons are not symmetrically arranged, a dipole moment exists. Since the moment is probably never exactly zero, the term "homopolar" is sometimes used in place of nonpolar to designate low polarity. Examples of substances which are virtually nonpolar are saturated hydrocarbons such as methane and hexane and some other symmetric molecules such as carbon tetrachloride, benzene, carbon dioxide, and acetylene.

If the molecular structure is known as for some simple molecules, the dipole moment can be calculated. For more complicated forms, dipole moments may be estimated from various formulas (ref. 17) which make use of the dielectric constant, index of refraction, density, molecular diameter, and molecular weight.

EXPERIMENTAL APPARATUS AND PROCEDURES

A diagram of the single-tube condenser used in the present condensation and heat-transfer experiments is shown in figure 3. A borosilicate glass tube with an inside diameter of 7.62 cm was chosen as the outer casing to permit visual observation of the condensing surface. Steel disks 2.54 cm thick and 12.70 cm in diameter were machined to fit into each end of the glass tube with O-ring seals to prevent vapor leakage. A 3.18-cm hole was drilled in the center of each steel disk to facilitate changing of the inner tube whose exterior served as the condensing surface. Cooling water flowed through the inside of the inner tube.

Two iron tubes were used. One was sanded as smooth as possible with No. 200 sandpaper and left uncoated. The other was coated with a uniform thickness of pure polytetrafluoroethylene, 0.038 cm thick on the exterior surface.

Teflon was selected as a condenser coating for several reasons: It had been used by others to promote dropwise condensation (refs. 7 and 8), it is nonpolar (ref. 18), it is very stable, and it is inert to all chemical reagents at ordinary temperatures. At temperatures above 149° C, it is attacked only by fluorine and molten alkali metals. It will continuously withstand temperatures of 260° C and for short times even higher temperatures up to the softening point at 326° C. Its smoothness and low coefficient of friction are also desirable. Its corrosion resistance and its insolubility in organic vapors suggest a promoter life in excess of the periods of the several hundred hours achieved by other promoters.

The equipment arrangement shown in figure 3 was used for the alcohols, acetone, and carbon tetrachloride. The condenser was mounted vertically. To maintain a constant pressure in the condenser and to prevent backflow of noncondensable air into the system, the end of the condensate outlet line was submerged to a depth of approximately 15 cm below the top of a small can, which was filled with the liquid being tested. As

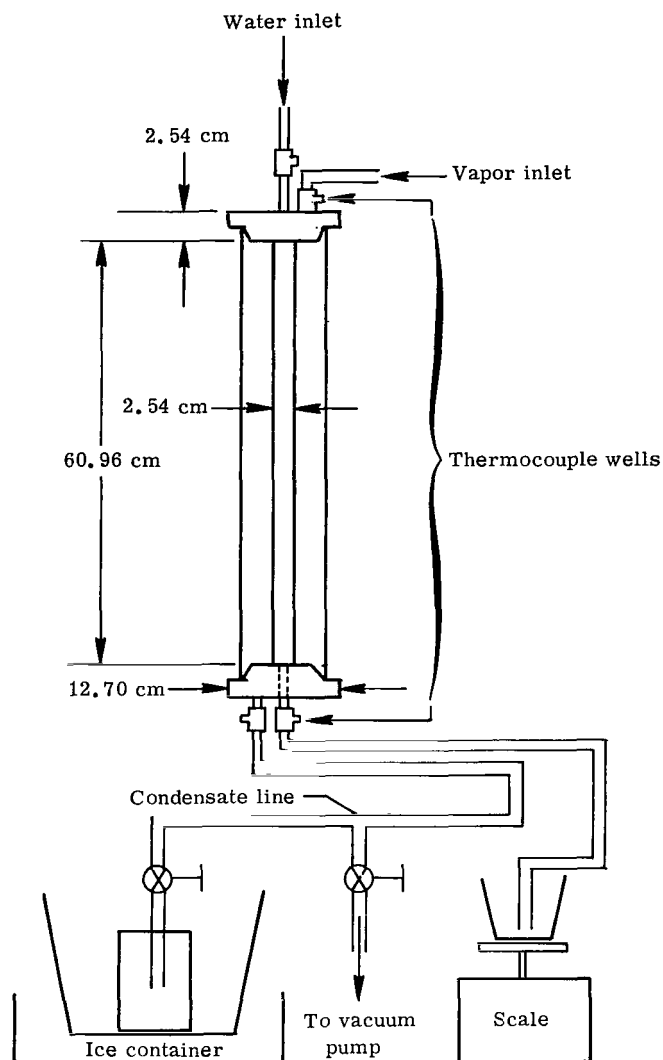


Figure 3.- Equipment diagram for condensation of organic vapors.

additional condensate came from the condenser the small can overflowed and thus maintained a constant depth for the condensate outlet line.

An experimental run was started by evacuating the condenser and its inlet and outlet lines, heating the liquid in a boiler until a positive pressure was achieved in the boiler, and admitting vapor from the boiler into the evacuated condenser system. When vapor was first admitted into the condenser, some condensation occurred on the inside of the glass tube. After several minutes the temperature of the glass increased and no further condensation occurred on its inner surface. The cooling-water flow rate was then adjusted until the temperature of the outgoing condensate was not less than 1.1°C below

the boiling point of the liquid under test. Simultaneous readjustment of the cooling-water flow rate and heat input to the boiler provided additional conditions for a range of data points.

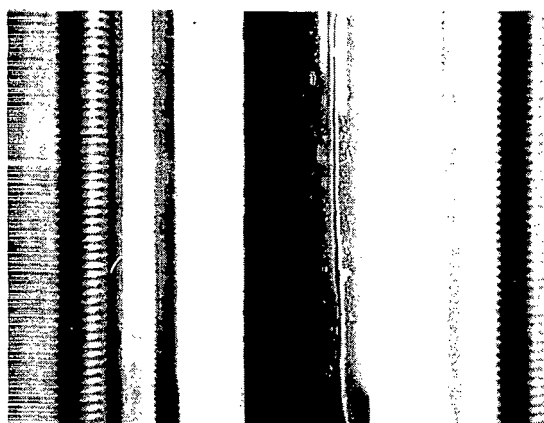
After sufficient time was allowed for steady-state conditions to be reached, temperatures of the cooling water at the inlet and outlet ends of the condenser were recorded. The cooling water was collected for a measured amount of time and weighed to determine the flow rate.

An overall heat-transfer coefficient for condensation U , calculated by the method shown in the appendix, was selected as a parameter for determining the relative increase in heat transfer with the teflon-coated tube over that with the uncoated tube. The overall heat-transfer coefficient is usually used by investigators concerned with methods of achieving dropwise condensation and with determining the resulting increases in heat-transfer rates (refs. 2, 3, and 19). The overall heat-transfer coefficient is also a common parameter used in the design of condensers (ref. 20). Admittedly, it is not an ideal choice because it is dimensional, but it is a practical necessity because of the large number of variables involved and because of the lack of understanding of the process and relative significance of each variable. Some of the factors which are believed to affect the process of dropwise condensation in addition to the ones already mentioned in the section "Review of Dropwise Condensation Theory" are vapor velocity, cooling-water velocity, temperature variations along the tube, temperature variations with time, surface roughness, condensate purity, surface orientation, and surface geometry. Possibly, several of the properties of the condensate such as thermal conductivity, specific heat, vapor pressure, surface tension, and density also affect the process. Until the relative significance of many of the relevant variables is determined, the overall heat-transfer coefficient will probably remain in use.

RESULTS AND DISCUSSION

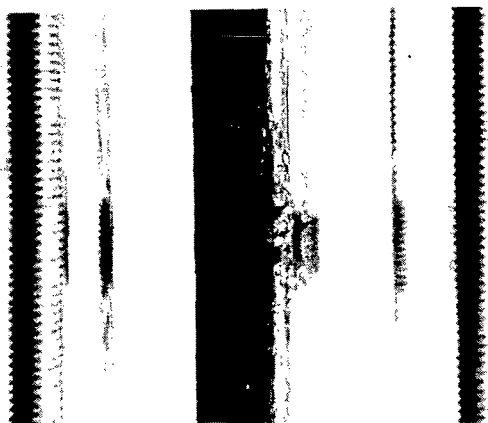
At the highest rates of condensation, good dropwise condensation was observed on the upper half of the tube nearest the vapor-inlet end of the condenser as shown in figure 4. From the approximate center of the tube to the outlet end, the "quality" of dropwise condensation decreased. At low vapor flow rates, good dropwise condensation covered the entire surface.

This "quality" is based on visual observation of the percentage of the tube area covered with drops. The percentage of the tube covered by a film increased toward the outlet end and the final 5 to 8 cm was almost completely covered with a film at high condensation rates. It is obvious that for vertically mounted condensers, as drops of liquid coalesce and run down the surface of the tube, there may be a buildup of liquid at the



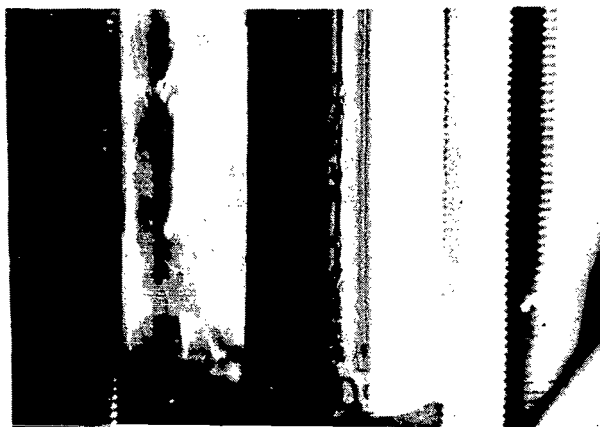
Entrance end
of condenser

Good dropwise
condensation



Center area

Mixed film
and dropwise
condensation



Exit end

Almost complete
film covers
surface

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Figure 4.- Dropwise condensation of methyl alcohol on teflon-coated surface.

lowest end of the tube. Some length will be reached at which the accumulated liquid from upper portions of the tube will be sufficient to cover the tube with a film.

The fact that part of the condensing surface was covered with a film, with its inherently lower heat-transfer rate, indicates that the experimentally measured increases in overall heat-transfer coefficient are of a composite nature since dropwise and filmwise condensation are occurring simultaneously on different portions of the tube. It was also noticed that if the rate of vapor input from the boiler was reduced while a high cooling-water flow rate was maintained, complete dropwise condensation covered the entire tube. When the vapor inputs were returned to the higher rates, a film reappeared near the lower end of the tube.

The overall heat-transfer coefficients for acetone at various cooling-water velocities are shown in figure 5. The overall heat-transfer coefficient for dropwise condensation was higher than that for filmwise condensation by approximately 65 percent.

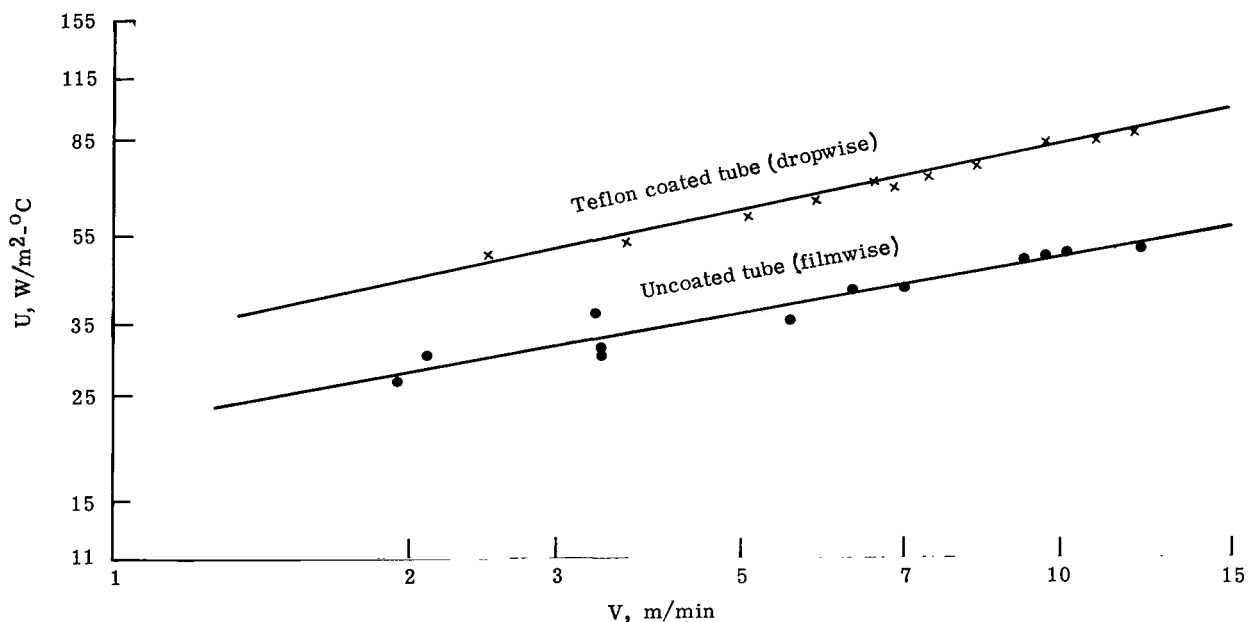


Figure 5.- Overall heat-transfer coefficient as a function of cooling-water velocity for condensation of acetone.

Figure 6 shows the heat-transfer results for methyl alcohol. The increase in the overall heat-transfer coefficient for dropwise condensation varied from 38 percent at a cooling-water velocity of 1.8 m/min to 51 percent at 14.1 m/min for an average increase of 45 percent.

The heat-transfer results for ethyl alcohol are shown in figure 7. The increase in the overall heat-transfer coefficient was approximately 30 percent.

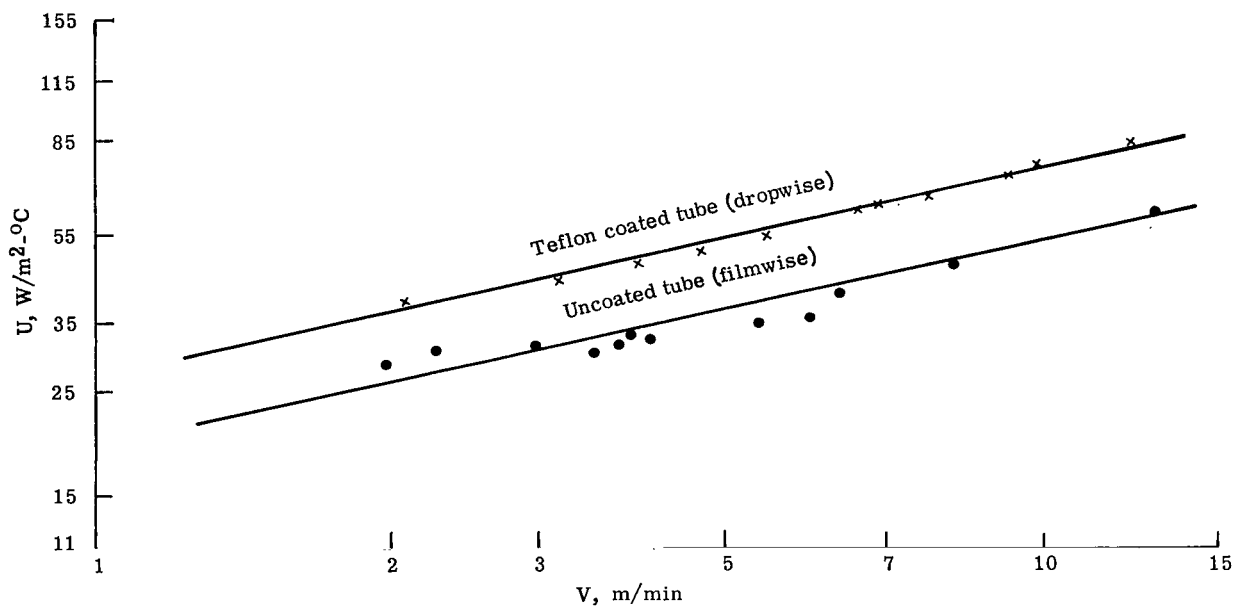


Figure 6.- Overall heat-transfer coefficient as a function of cooling-water velocity for condensation of methyl alcohol.

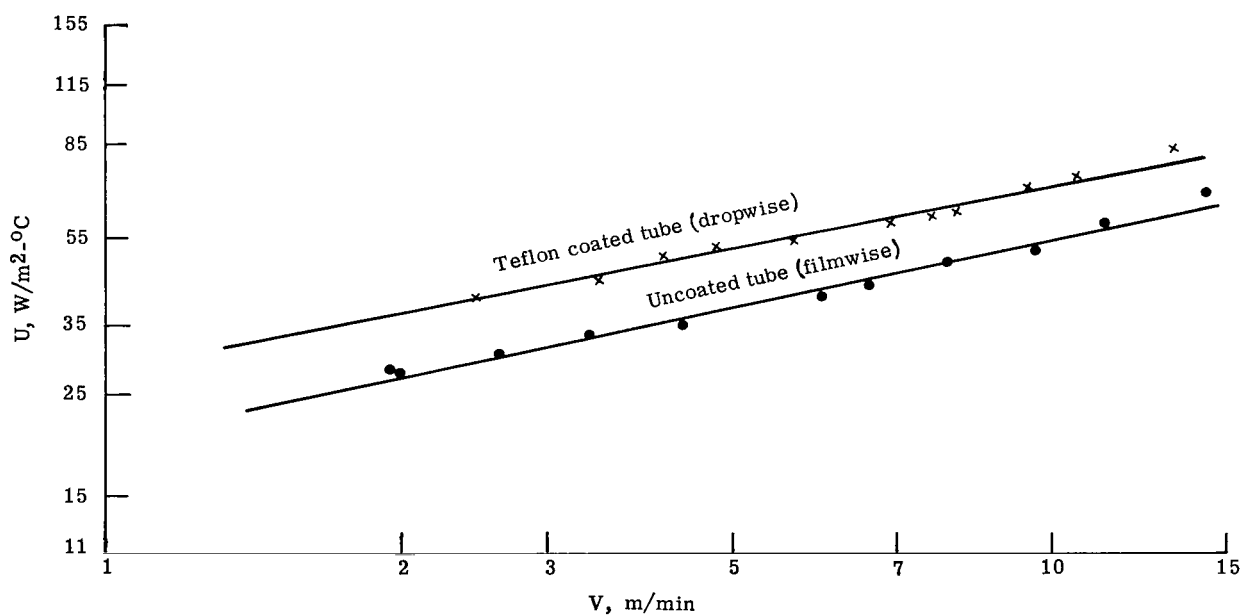


Figure 7.- Overall heat-transfer coefficient as a function of cooling-water velocity for condensation of ethyl alcohol.

A summary of the type of condensation which occurs on a teflon surface is shown in table 1. The liquids with a net dipole moment greater than 1.5 Debye units (1 Debye unit = 10^{-18} statcoulomb-cm = 3.3356×10^{-28} coulomb-cm) condensed dropwise and those with zero dipole moment condensed filmwise. The dipole moments given in the table are from reference 21. The surface tensions (from ref. 22) of ethyl alcohol, methyl alcohol, acetone, and carbon tetrachloride, at their boiling points, are all within the range from 17.5 to 20.5 dynes/cm, which is the band of critical surface tension for condensation on teflon. Benzene, aniline, ethylene glycol, and nitrobenzene all have surface tensions greater than 20.5 dynes/cm and therefore should condense dropwise according to the critical-surface-tension criterion. However, reference 8 shows that benzene condenses filmwise on teflon. The concept of critical surface tension in its present form does not appear to be applicable in predicting dropwise condensation of organic liquids on teflon. If data were available for the spreading of liquids on the teflon surface at temperatures near the boiling points of the liquids rather than at 20° C only, the concept of critical surface tension might be more applicable to dropwise condensation.

The critical-surface-tension experiments of reference 16 were performed at 20° C. It is probably more appropriate for condensation studies to consider the surface tension at the boiling point of the liquid being condensed, as just discussed. However, even if surface tensions at 20° C are considered as shown in the fourth column of table 1, the results still do not correlate satisfactorily. Based on liquid surface tensions at 20° C on a teflon surface at 20° C, all the liquids should condense dropwise on teflon since their surface tensions are then greater than 20.5 dynes/cm, but benzene and carbon tetrachloride condensed filmwise.

Since Blackman and coworkers (ref. 3) have also found that whether a condensing surface is polar or nonpolar determines the type of condensation which occurs with steam, the true relationship of dipole moment in dropwise condensation seems worthy of further study. Particular emphasis should be placed on liquids of dipole moment between 0 and 1.5 Debye units. The existence of a critical dipole moment, somewhat analogous to the concept of critical surface tension, seems likely for organic liquids condensing on a teflon surface. Liquids such as thiophene (0.54 Debye units), trichloroethylene (0.8 Debye units), ethylene chlorobromide (1.11 Debye units), and ethylamine (1.37 Debye units) could be investigated. Others such as n-hexane could be investigated for additional verification that nonpolar liquids condense filmwise on a teflon surface. These could be used with plastics of relatively low critical surface tensions, such as polyethylene or polypropylene, to evaluate the true relationship of polar moment in dropwise condensation.

At the time these experiments were performed, the only liquid which was within the range of dipole moment from 0 to 1.5 Debye units, was readily available, and would not require extensive modification to the equipment was trichlorofluoromethane (Freon-11). The Freon-11 condensed as a film on the teflon and on the bare iron tube.

A possible explanation of why the dipole moment may have an effect on dropwise condensation could be related to the process of molecular association. Polar molecules with their resultant positive charges on one end and negative charges on the other tend to be attracted to each other in a manner favoring the greatest attractive forces and thus form groups of molecules. The process may continue until very large aggregates are formed. It is conceivable that enough molecules could join together to form a drop nucleus.

CONCLUDING REMARKS

Experimental overall heat-transfer coefficients are presented for the dropwise condensation of ethyl alcohol, methyl alcohol, and acetone on a teflon-coated condensing surface and for filmwise condensation on a bare iron tube. The composite overall heat-transfer coefficients during dropwise condensation are approximately 30 percent greater for ethyl alcohol, 45 percent greater for methyl alcohol, and 65 percent for acetone than those during filmwise condensation on the bare iron tube. Since even in the case of dropwise condensation, a film covered the lower portion of the heat-transfer surface, the observed increases in the overall heat-transfer coefficient are not as large as the increases which would occur had the film not been present.

Results from this investigation along with a study of previously reported experimental results show that the type of condensation which occurs from organic vapors on teflon condensing surfaces may depend on the dipole moment of the organic molecule. Nonpolar organic vapors tend to condense filmwise whereas vapors with a strong dipole moment tend to condense dropwise.

A brief discussion of some concepts from the theory of adhesives is included. Research results on surface wetting from the adhesives field may be a fruitful source of guidance for the required future research to verify the presumed relationship of dipole moment to surface polarity in obtaining dropwise condensation.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., May 25, 1971.

APPENDIX

CALCULATION OF OVERALL HEAT-TRANSFER COEFFICIENTS

The procedure for calculating overall heat-transfer coefficients from raw data is given in this appendix. Table 2 gives raw data for the dropwise condensation of acetone, for example, on the teflon-coated tube. The following data are from the first row in table 2:

Temperature of vapor at inlet, T_{v1} , °C	62.5
Temperature of vapor at outlet, T_{v2} , °C	55.8
Temperature of water at inlet, T_{w1} , °C	30.3
Temperature of water at outlet, T_{w2} , °C	40.0
Water flow rate, w , g/min	885
Temperature change of water, °C	9.7

where the subscript 1 denotes the inlet end of the condenser and the subscript 2 denotes the outlet end.

The equation for the logarithmic mean temperature difference ΔT_m is

$$\Delta T_m = \frac{(T_{v1} - T_{w1}) - (T_{v2} - T_{w2})}{\ln \left(\frac{T_{v1} - T_{w1}}{T_{v2} - T_{w2}} \right)}$$

Substitution of the inlet and outlet temperatures just listed gives

$$\Delta T_m = \frac{(62.5 - 30.3) - (55.8 - 40.0)}{\ln \frac{(62.5 - 30.3)}{(55.8 - 40.0)}} = 23.0^\circ \text{ C}$$

The equation for the quantity of heat added to the cooling water is

$$\begin{aligned} Q &= wc_p \Delta T \\ &= (885 \text{ g/min}) \left(\frac{1 \text{ cal}}{\text{g} \cdot ^\circ \text{C}} \right) (9.7^\circ \text{ C}) \left(\frac{60 \text{ min}}{\text{hr}} \right) \\ &= 5.14 \times 10^5 \text{ cal/hr} \\ &= 598 \text{ watts} \end{aligned}$$

APPENDIX - Concluded

The surface area of the tube A_S is equal to π times the outside diameter times the length:

$$A_S = \pi(2.54)(61) = 486 \text{ cm}^2$$

The overall heat-transfer coefficient U is

$$\begin{aligned} U &= \frac{Q}{A_S \Delta T_m} \\ &= (598 \text{ watts}) \left(\frac{1}{486 \text{ cm}^2} \right) \left(\frac{1}{23^\circ \text{ C}} \right) \\ &= 535 \text{ watts/m}^2\text{-}^\circ\text{C} \end{aligned}$$

The water velocity is calculated from the flow rate (for the tube with an inside diameter of 2.09 cm) as follows:

$$\begin{aligned} A_i &= \frac{\pi(\text{diameter})^2}{4} = \frac{\pi(2.09)^2}{4} = 3.43 \text{ cm}^2 \\ V &= (885 \text{ g/min}) \left(\frac{1}{3.43 \text{ cm}^2} \right) \left(\frac{1}{1 \text{ g/cm}^3} \right) \left(\frac{1 \text{ m}}{100 \text{ cm}} \right) \\ &= 2.58 \text{ m/min} \end{aligned}$$

These values of U and V are plotted as one point in figure 5. Other points on the curves are obtained similarly.

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TABLE 1.- ACTUAL AND PREDICTED CONDENSATION OF SOME ORGANIC LIQUIDS ON A TEFLON SURFACE

Liquid	Boiling point, bp °C	Surface tension at bp, dynes/cm	Surface tension at 20° C, dynes/cm	Type of condensation on teflon	Dipole moment at 20° C, Debye units	Predicted condensation based on dipole moment	Predicted condensation based on surface tension at bp
		(a)	(a)	(b)	(c)		
Ethyl alcohol	78.4	17.5	22.3	Dropwise	1.69	Dropwise	Undefined
Methyl alcohol	64.7	18.8	22.6	Dropwise	1.69	Dropwise	Undefined
Acetone	56.5	18.6	23.7	Dropwise	2.80	Dropwise	Undefined
Carbon tetrachloride	76.8	20.0	26.8	Filmwise	0	Filmwise	Undefined
Benzene	80.1	21.3	28.9	Filmwise	0	Filmwise	Dropwise
Aniline	184.4	24.0	42.9	Dropwise	1.52	Dropwise	Dropwise
Ethylene glycol	197.4	32.7	47.7	Dropwise	2.30	Dropwise	Dropwise
Nitrobenzene	210.9	21.8	43.9	Dropwise	3.96	Dropwise	Dropwise
Trichlorofluoromethane	26.8	---	19.9	Filmwise	.45	Dropwise	Undefined

^aLinear extrapolation or interpolation of data from reference 22.

^bFirst four observed by author; remaining five from reference 8.

^cFrom reference 21. 1 Debye unit = 10^{-18} statcoulomb-cm = 3.3356×10^{-28} coulomb-cm.

TABLE 2.- RAW DATA FOR DROPWISE CONDENSATION OF ACETONE

Water velocity, m/min	Water temperature at inlet, °C	Water temperature at outlet, °C	Vapor temperature at inlet, °C	Vapor temperature at outlet, °C	Water flow rate, g/min
2.58	30.3	40.0	62.5	55.8	885
5.14	29.9	36.4	62.0	55.2	1640
5.96	29.9	35.5	62.0	55.2	1910
6.97	29.1	34.7	61.5	54.6	2230
7.83	28.8	34.1	61.5	54.6	2510
8.77	28.0	32.9	61.5	54.6	2810
11.8	27.7	32.1	62.0	54.6	3770
3.77	29.6	37.4	62.5	55.2	1200
7.21	28.8	34.4	62.5	55.8	2300
1.03	28.2	33.3	62.5	55.8	3280
1.28	28.0	32.1	62.5	55.8	4100

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